Warm Pressurant Gas Effects on the Static Bubble Point Pressure for Cryogenic LADs

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Outline

Background

- Liquid Acquisition Devices
- The Bubble Point Pressure
- LAD/Pressurization System Interaction

Test Description

- Experimental Design
- Experimental Procedure

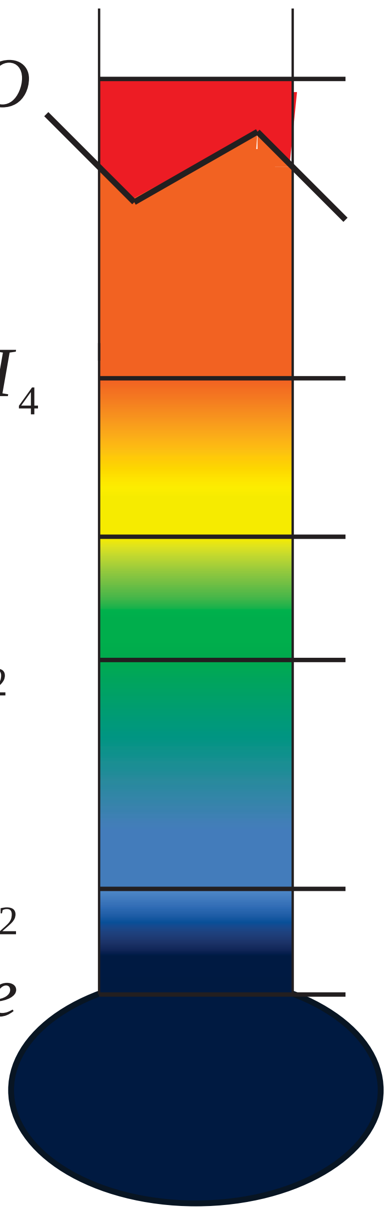
Results

- Test Conditions
- Cold Pressurant Gas Tests
- Warm Pressurant Gas Tests

Conclusions/Implications

Background

Fundamental Cryogenic Fluids



Triple Line T [K]	NBP [K]	T_C [K]	σ @ NBP [mN/m]
273.2	373.2	647.1	65.6
88.7	111.7	190.7	13.3
54.4	90.2	154.6	13.2
63.2	77.3	126.1	8.9
13.9	**20.4**	**33.2**	**1.9**
2.2	4.2	5.2	0.092

PMD Overview – Fundamental Fluid Physics

Subsystem requirement - transfer single phase propellant from a tank to the transfer line en route to an engine or receiver tank

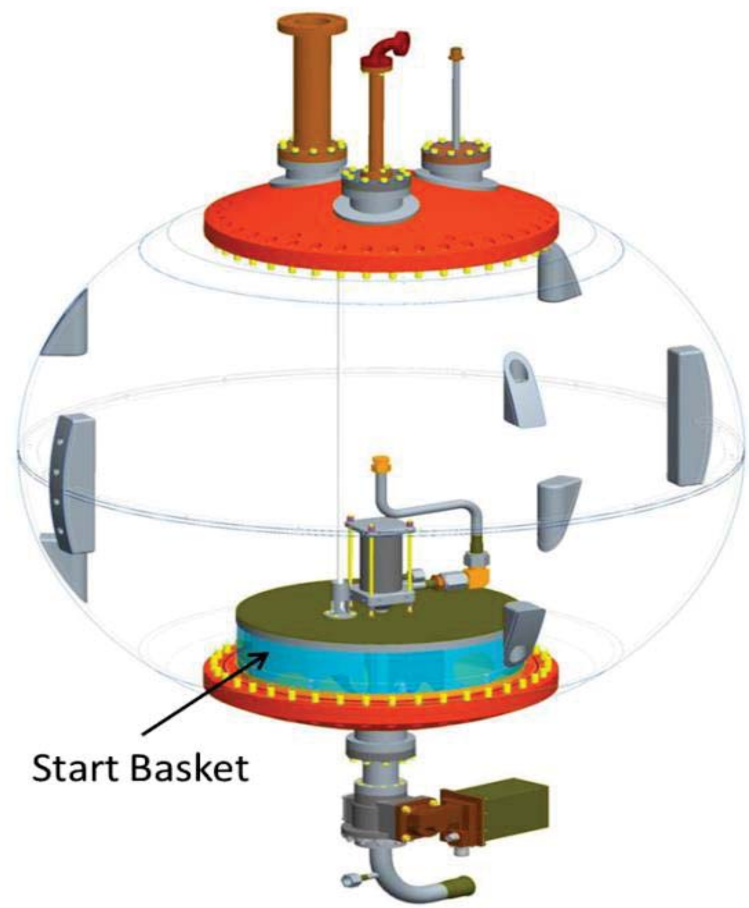
Separation of liquid and vapor phases governed by lowest achievable potential energy state

1-g or milli-g Fluid transfer

- Gravitational force is the driver
- Liquid → bottom, vapor → top

Single phase flow strategy:

- Settling thrusting maneuvers
- Anti-vortex baffle and/or sump



PMD Overview – Fundamental Fluid Physics

<u>Subsystem requirement</u> - transfer vapor free propellant from a tank to the transfer line en route to an engine or receiver tank (depot)

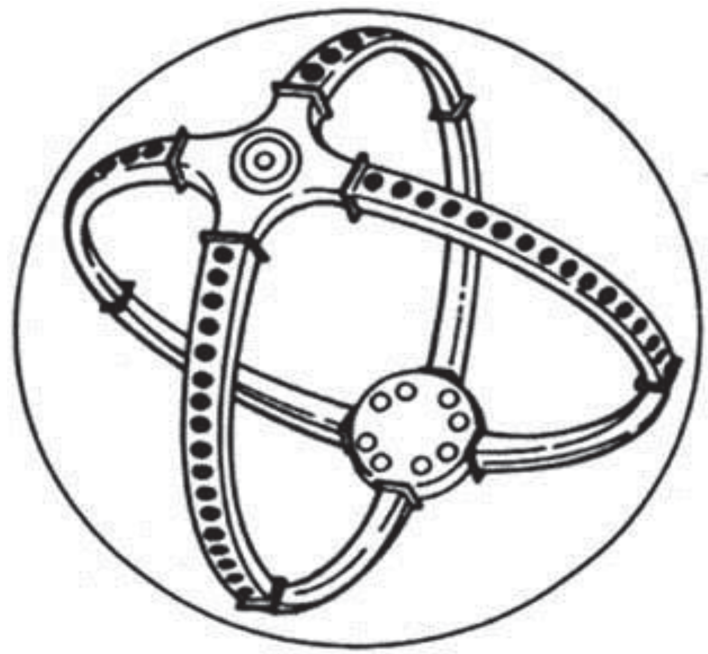
Separation of liquid and vapor phases governed by lowest achievable potential energy state

μ-g Fluid transfer

- Surface tension force is the driver
- Liquid → outer walls , vapor → center

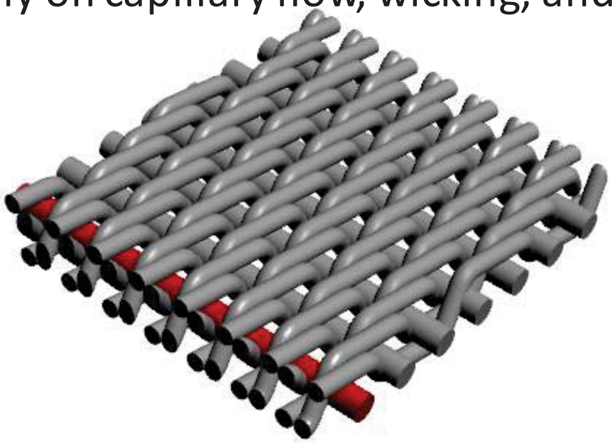
Single phase flow strategy:

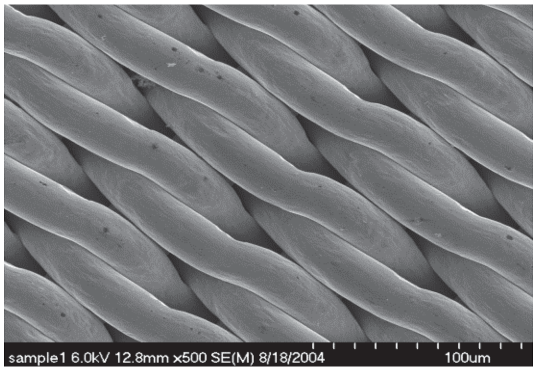
- Full "communication" device – usually a fine mesh or vane alongside tank wall
- Micron sized pores in screen:
  - allow liquid to flow into channel (L/L)
  - block vapor penetration (V/L)
  - wick liquid along screen (evaporation)



Screen Channel Liquid Acquisition Devices

- Screen channel liquid acquisition devices (LADs) or gallery arms are best in multi-directional, multi-g environments, high flow rates
- Warp/shute wires characterize the mesh (ex. 450x2750)
- LADs rely on capillary flow, wicking, and surface tension forces to maintain liquid flow





- Screen channel LADs fail when vapor is ingested across the screen during liquid outflow: $\Delta P_{total} > \Delta P_{BP}$

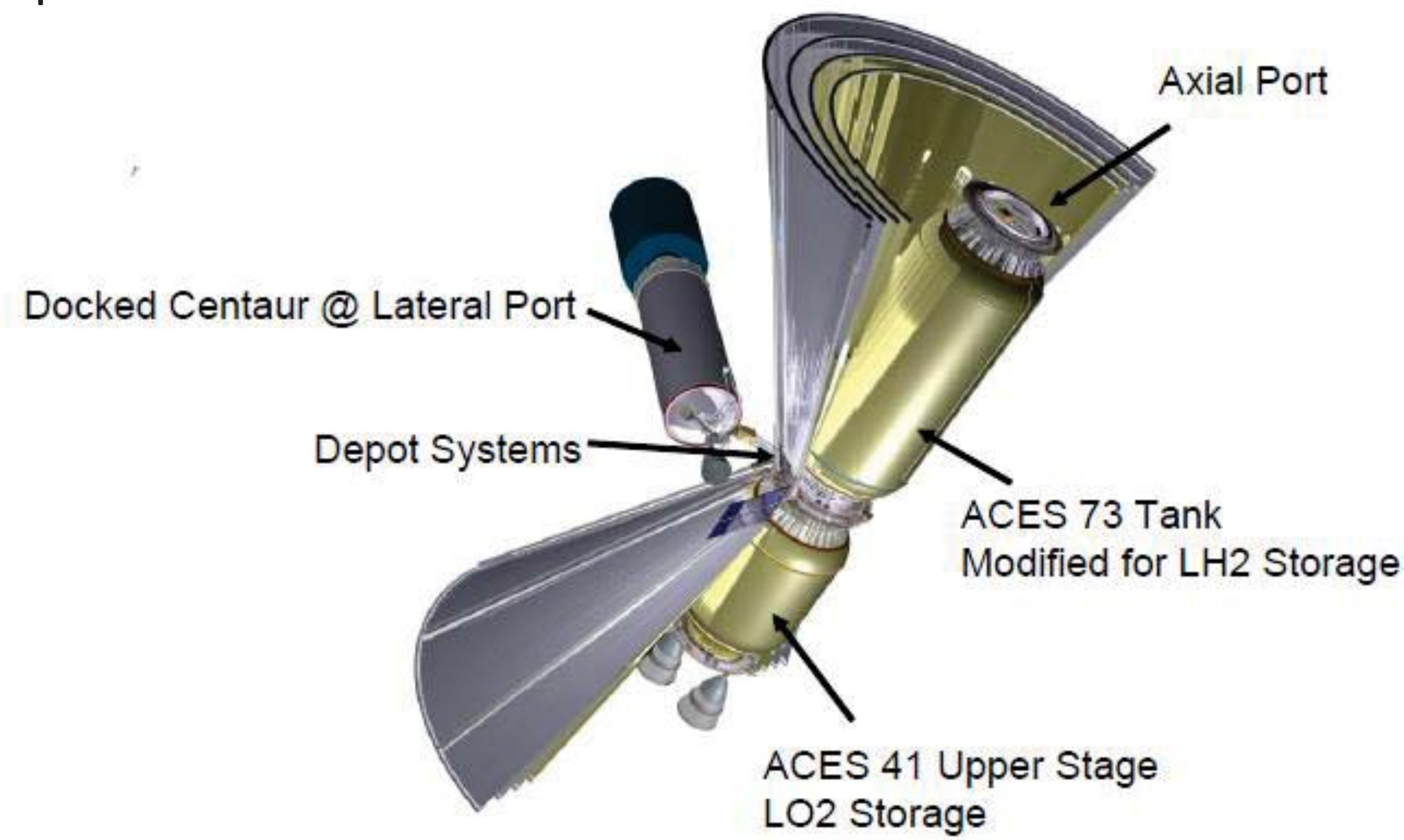
- Differential pressure across a screen pore that overcomes the surface tension of the liquid at that pore:

$$\Delta P_{BP} = \frac{4\gamma_{LV}}{D_P(T)}$$

- Bubble point pressure controls performance of LAD
- Small pore diameters (< 20 µm) may be favorable for LH_2 systems to counter low surface tension (2 mN/m)
- LH2 bubble point at 20K for a 325x2300 screen is only 575 Pa (0.08 psi)

LAD Applications - Cryogenic Propellant Depots

- Two “customers” – small scale cryo prop. engines (RCS), cryo fueled depots
- Depots will reside in LEO (10^{-6} g) for 0.5-2 years
- Example depot architecture:



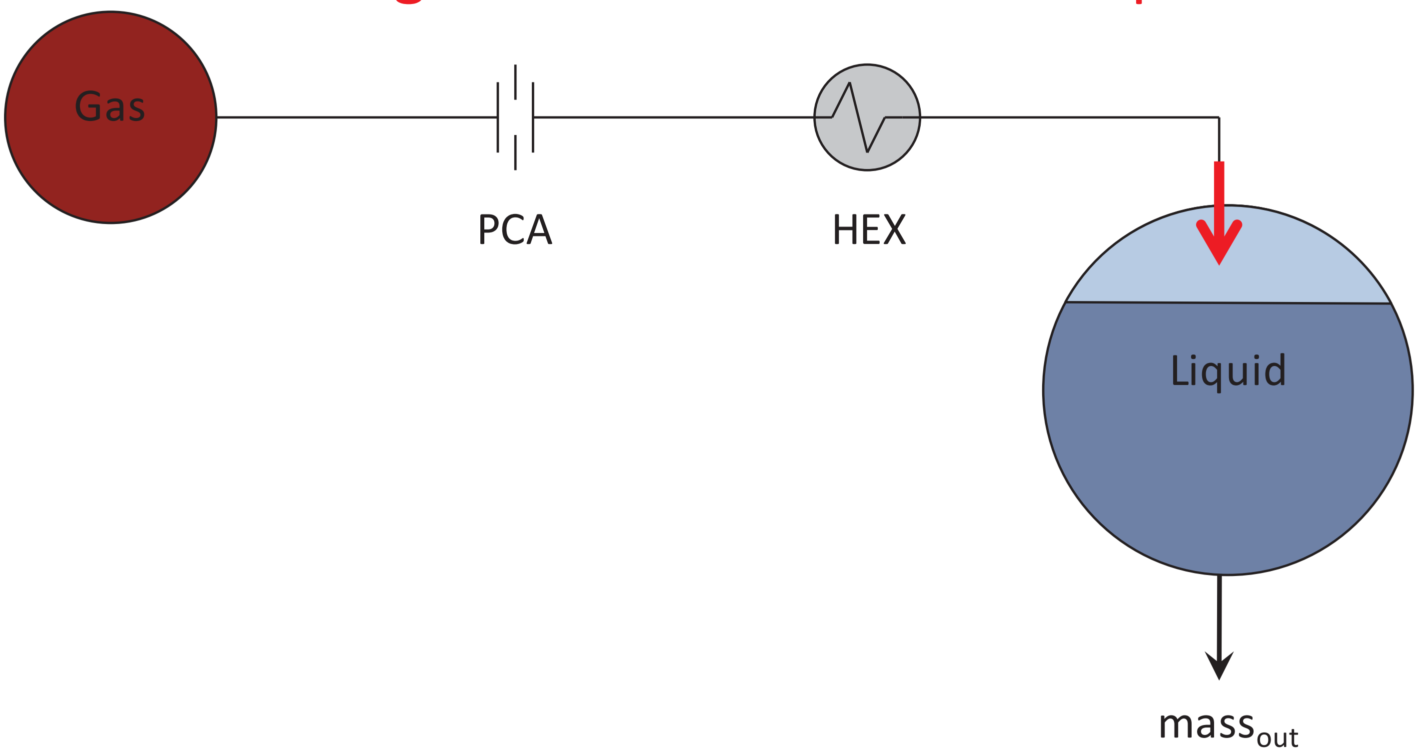
Credit: ULA

- 20 K storage and transfer issues must be addressed
- Not shown are pressurant gas bottles

LAD/Pressurization System Interaction

Two primary sources of heat leak into any flight tank

1. Storage – Through tank walls (MLI), penetrations, struts
2. Transfer – Through heat transfer between pressurant gas and liquid.



LAD/Pressurization System Interaction

Two primary sources of heat leak into any flight tank

2. Transfer – Through heat transfer between pressurant gas and liquid

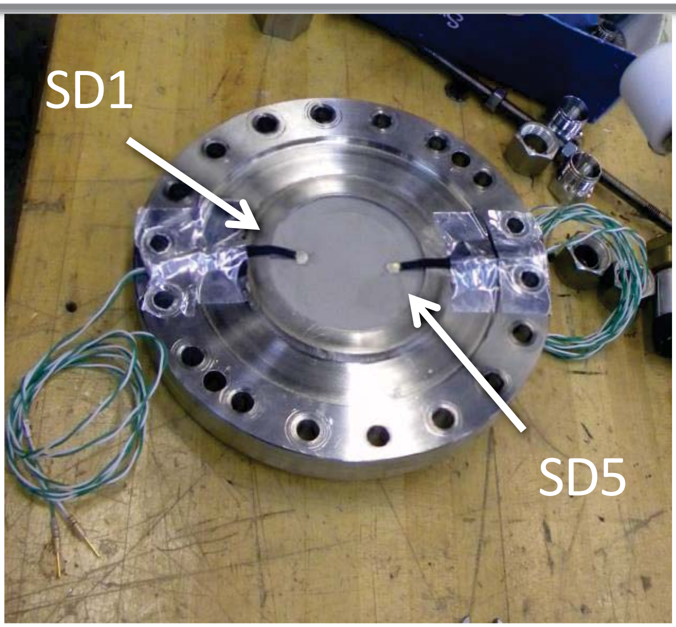
- Typically, pressurant gas temp. assumes environment temp.
- Even if COPV tank and prop. tank are thermally linked, T_{GAS} always > than T_{LIQUID}
- Warm gas (GHe or GH2) will always act to degrade performance of LAD due to added heat transfer

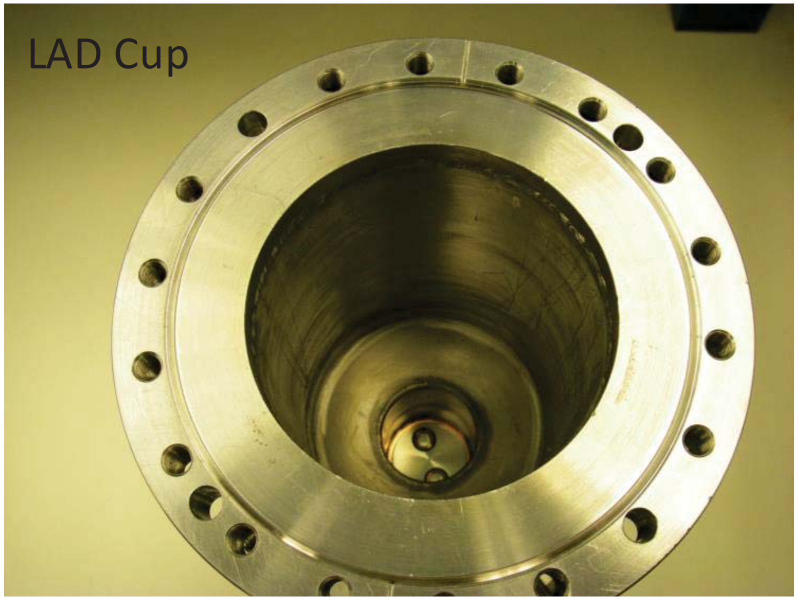
So what is the effect of warm gas on the already low LH2 bubble point?

Test Description

Experimental Design – LAD screen/cup

- Static inverted configuration
- Screen welded to flange, flange mounted to cup
- Purpose of the cup is to create L/V interface by pressurizing underside of screen
- Effective screen surface area = 4.90 in^2 (31 cm^2)
- Lines for inlet gas, drain



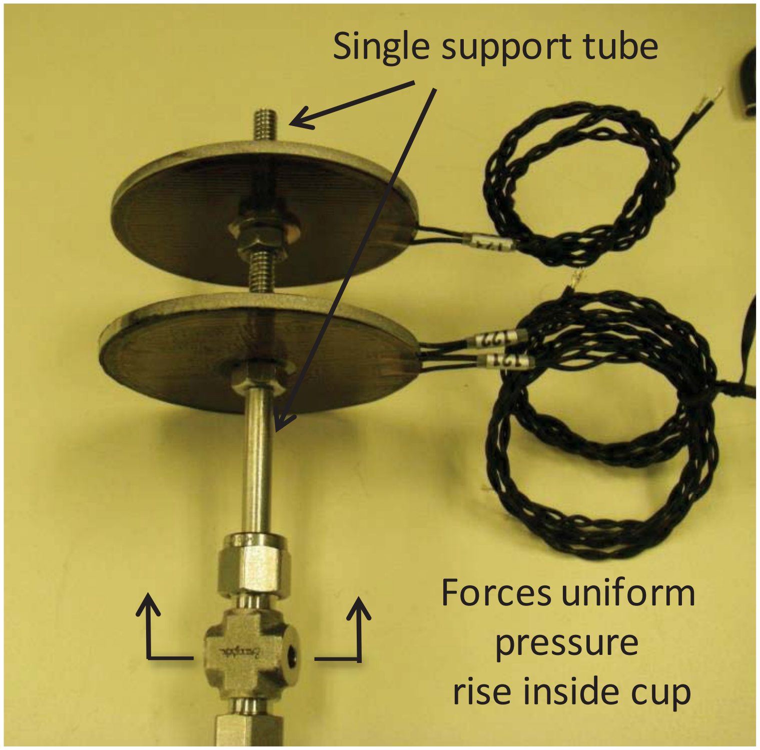


Measurements

T: L (2) and V (1) side of screen, pressurant gas (2)

P: DPT across screen 0-1250,0-2500 Pa

Experimental Design – LAD screen/cup

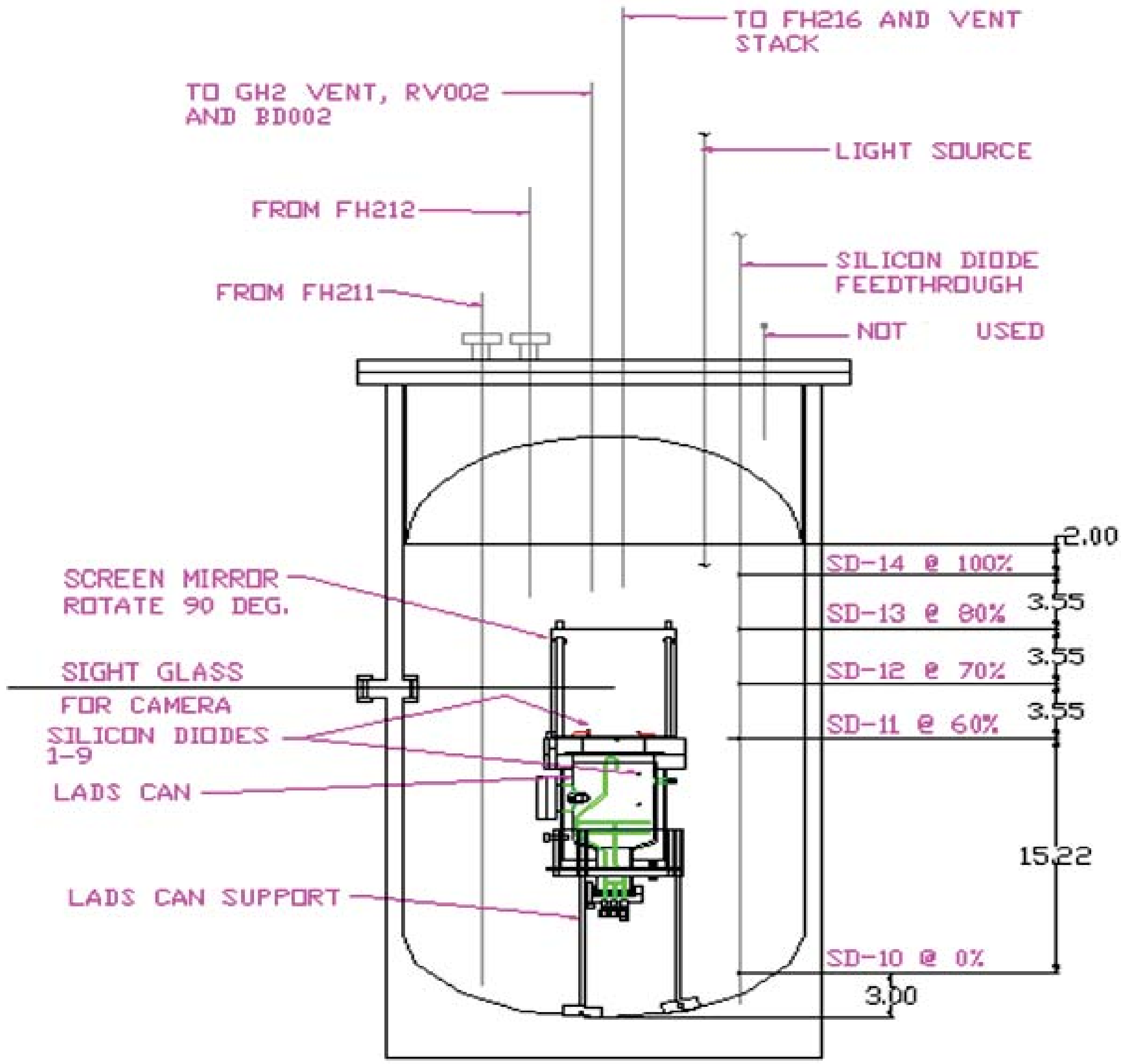


-Plates block view factor between heater and screen.
-175W of heating controlled using PID w/ SDs as feedback
-Configuration simplifies interpretation of effect of warm pressurant gas; maximizes natural convection, minimizes forced

Experimental Design – Receiver Dewar

- Purpose of RD is to contain liquid on top of LAD screen

- Mirror mounted on top of LAD to optimize image to external CCD camera
- Fiber optic light source illuminates a polished mirror
- Viewport for camera located 22'' high
- Video and DAQ time synched



[Measurements]

T: Bulk liquid (5)

P: Ullage, head

Experimental Procedure

Bubble Point Tests

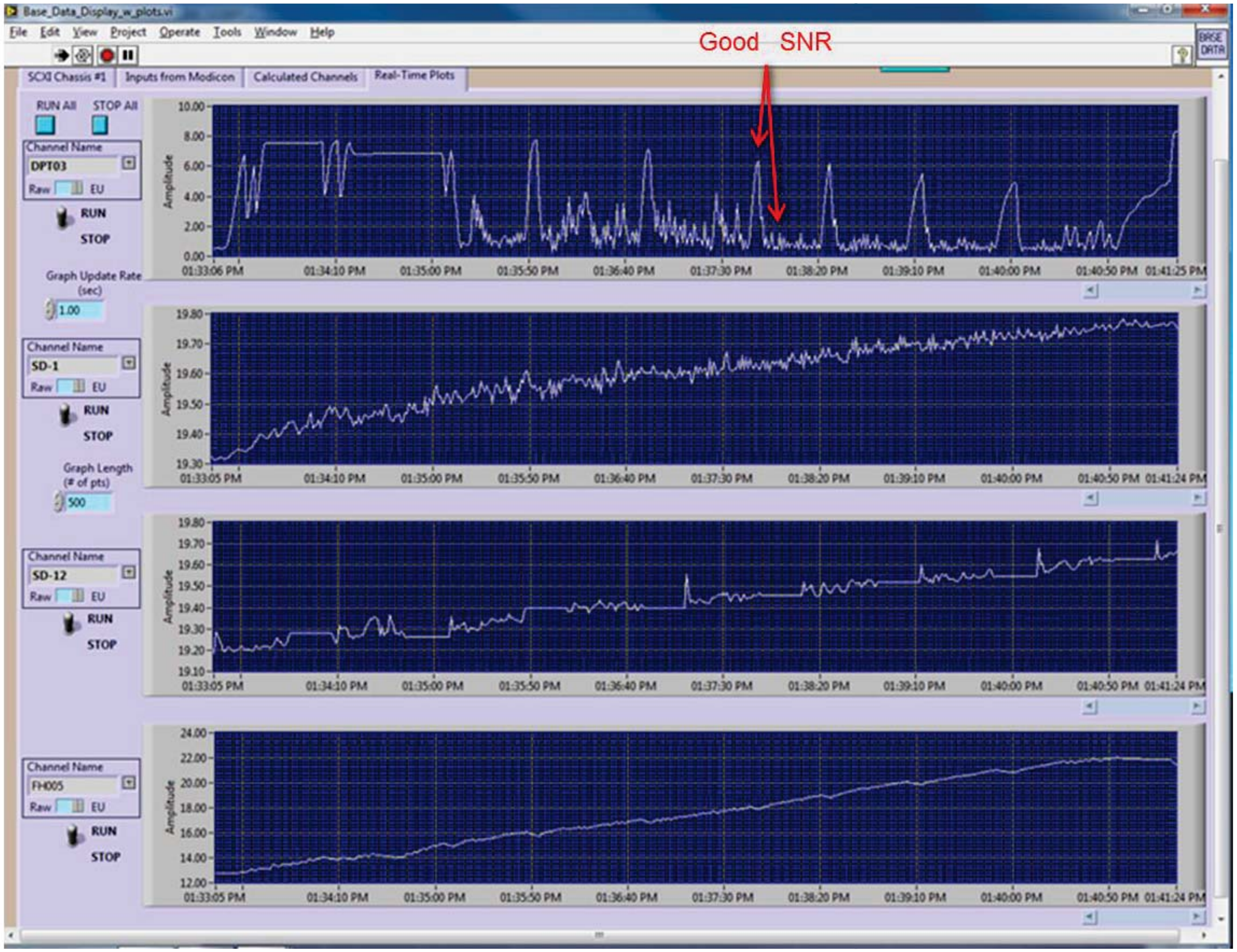
1. Fill dewar with LH2, seal screen
2. Warm the pressurant gas
3. Slowly increase pressure underneath screen until breakdown
4. Note the time at breakthrough, correlate with the data file
5. Reseal the screen, vent off pressure, repeat

DPT across screen

Liquid screen side temperature

Bulk liquid temperature

Ullage pressure



Results

Heated Gas Test Conditions

Parametrically investigate the effect of 6 different factors on bubble point pressure:

1. Screen Mesh
2. Liquid
3. Liquid Temperature
4. Liquid Pressure
5. Pressurant Gas Type
6. Pressurant Gas Temperature

For heated gas tests, first 5 parameters are fixed for each gas temperature

Three screens:
325x2300,
450x2750,
510x3600

Two liquid:
LH_2 LN_2

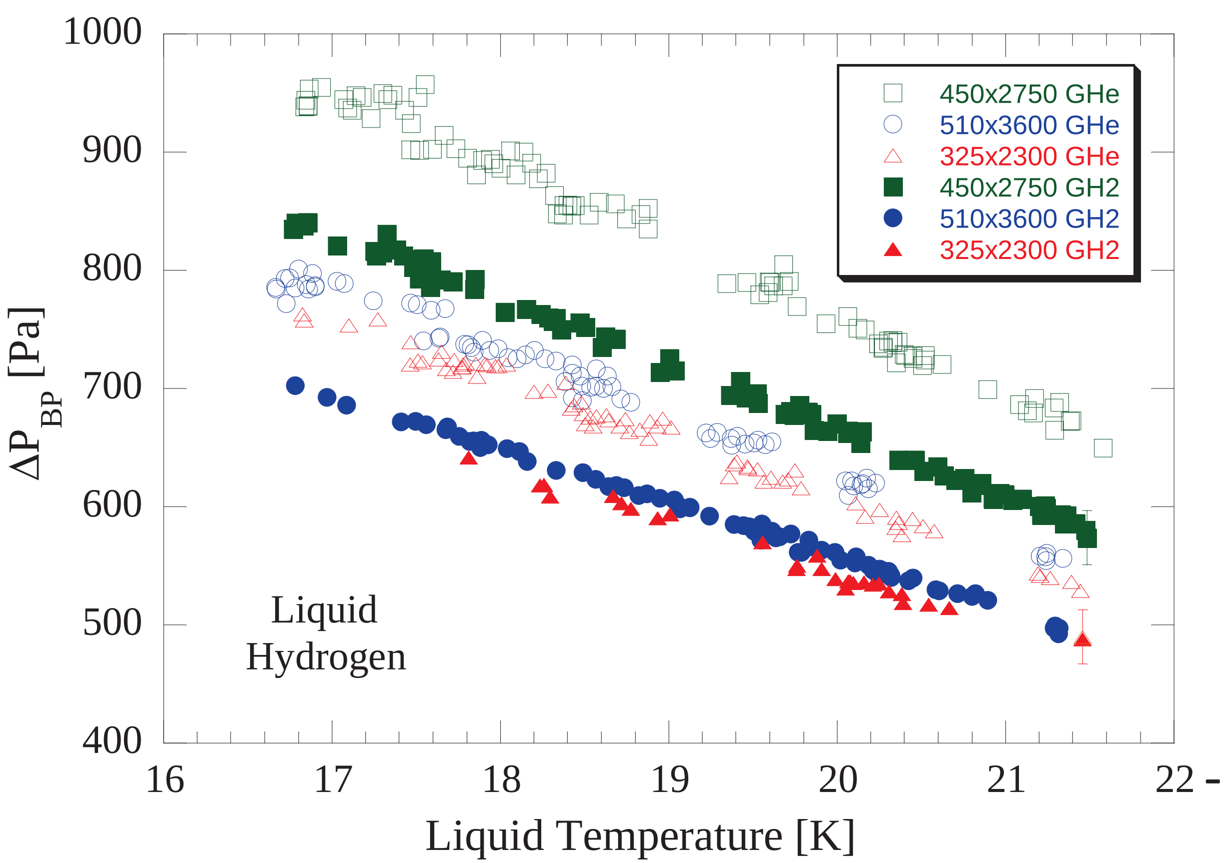
Two Pressurization Gases:
GHe, GH_2 (or GH_2)

Several Different Gas Temps
20K < Tgas < 110K

Liquid Hydrogen Cold Gas Tests

$$\Delta P_{BP} = \frac{4\gamma_{LV}\cos\theta_C}{D_P}$$

- 4/6 parameters summarized
- For all points here, $T_{GAS} = T_{LIQUID}$



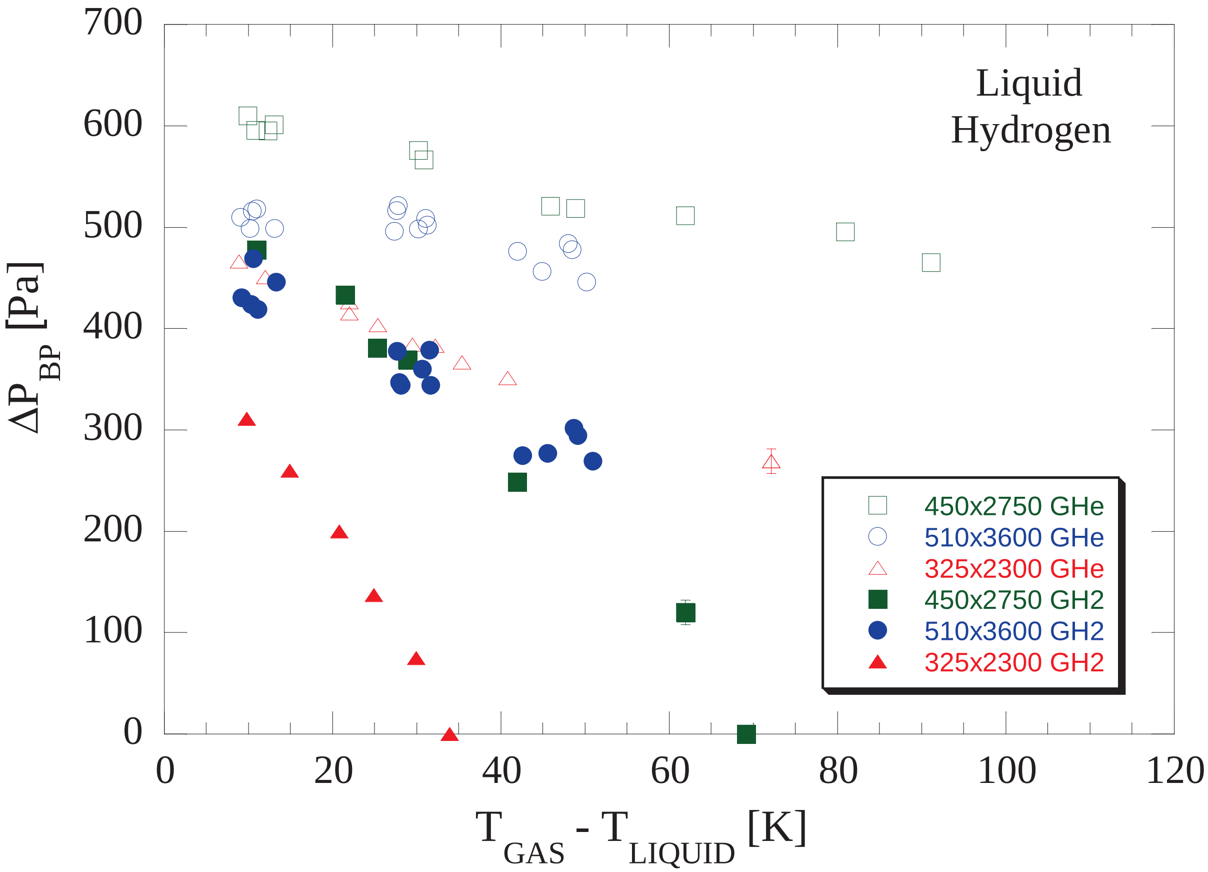
Trends

1. $\Delta P_{BP} \propto \dfrac{1}{D_P}$
2. $\Delta P_{BP} \propto \gamma_{LV}\cos\theta_C$
3. $\Delta P_{BP} \propto \dfrac{1}{T_{LIQ}}$
4. $\Delta P_{BP,GHe} > \Delta P_{BP,GH2}$
5. *P dependence alters T dependence* (Evaporation/condensation)

- Highest ΔP_{BP} @ coldest states using noncondensible pressurant with finest mesh

Liquid Hydrogen Warm Gas Tests

$$\Delta P_{BP} = \frac{4\gamma_{LV}\cos\theta_C}{D_P}$$



- $\Delta T = T_{GAS} - T_{LIQUID}$
- Warm gas data: 30K < T_{GAS} < 116K
- Liquid temp is fixed
- GHe and GH2 breakthrough data
- 10% uncertainty @ lowest ΔP_{BP}

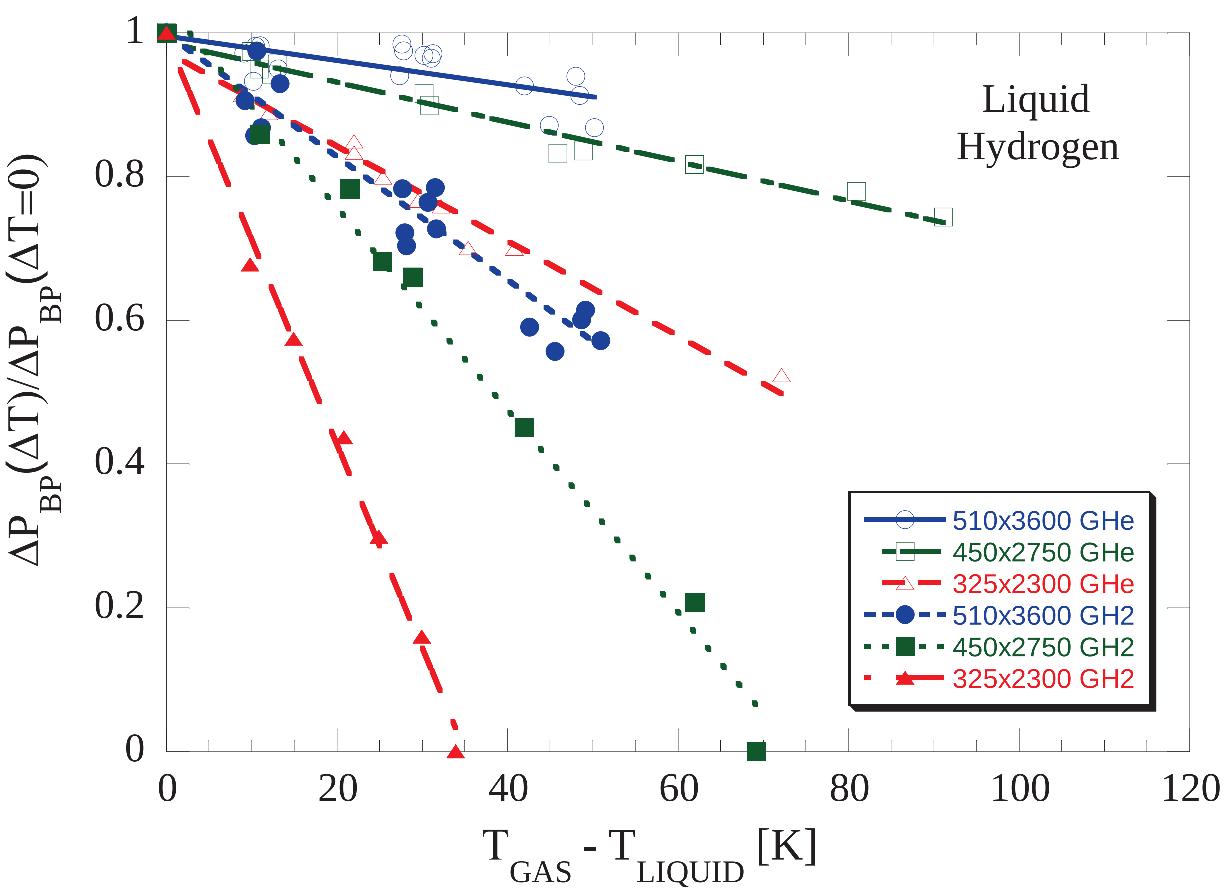
Trends

- $\Delta P_{BP} \propto \dfrac{1}{T_{GAS}}$ for all meshes
- Immediate onset of degradation for all screens and gases
- Degradation using GH2 > GHe
- Ex: compare 510 to 450

Liquid Hydrogen Warm Gas Tests

$$\frac{\Delta P_{BP}\left(\Delta T\right)}{\Delta P_{BP}\left(\Delta T=0\right)}=\left(1-n_{screen,gas}\left(T_{GAS}-T_{LIQUID}\right)\right)$$

- Warm gas data normalized by cold gas value



Trends

1. Elevating the gas temperature = degradation factor for all meshes, both pressurization schemes

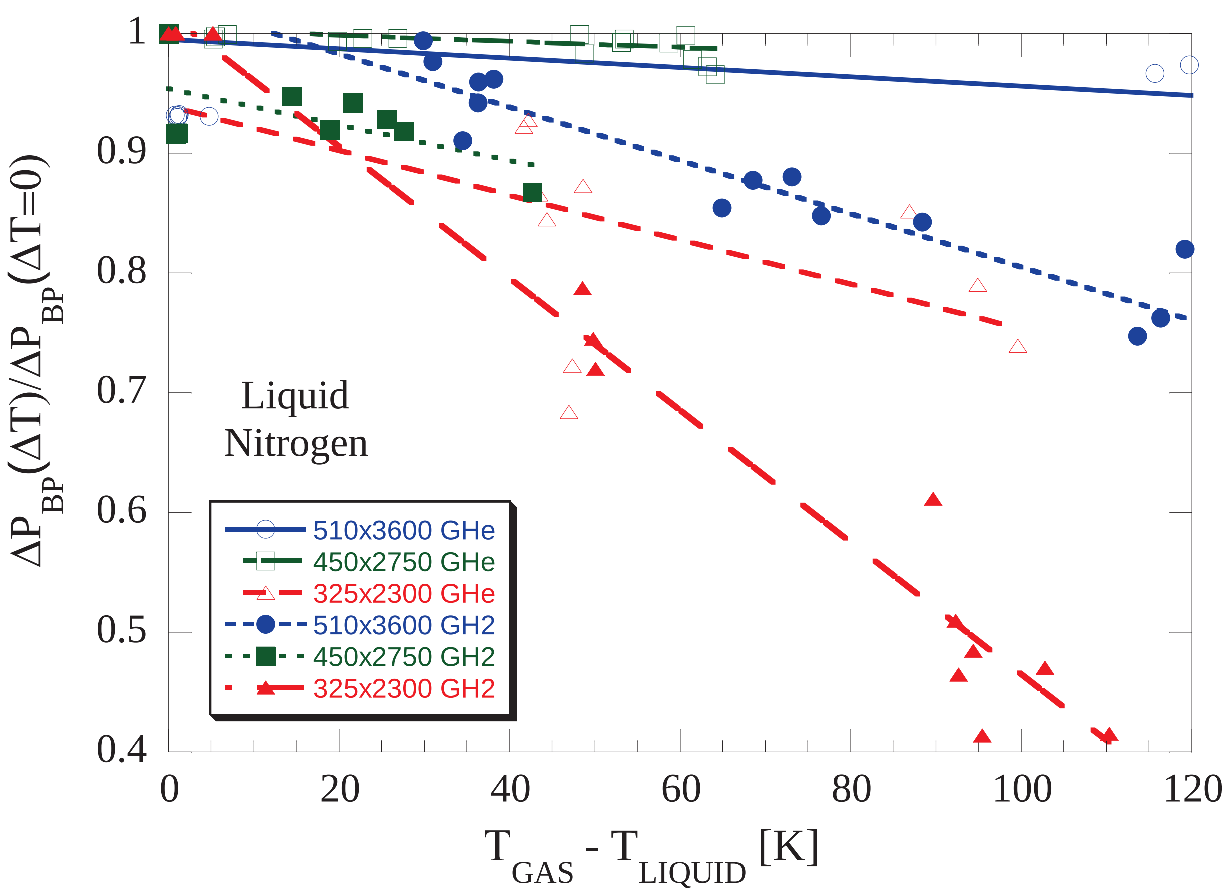
2. $n_{GH2} > n_{GHe}$

3. $n_{325} > n_{450} > n_{510}$

Liquid Nitrogen Warm Gas Tests

$$\frac{\Delta P_{BP}\left(\Delta T\right)}{\Delta P_{BP}\left(\Delta T=0\right)}=\left(1-n_{screen,gas}\left(T_{GAS}-T_{LIQUID}\right)\right)$$

- Warm gas data normalized by cold gas value



Trends

1. Onset of degradation is delayed in liquid nitrogen
2. $n_{GN2} > n_{GHe}$
3. $n_{325} > n_{450} > n_{510}$

Warm Pressurant Gas Trends

Liquid cryogen

- LN2 has higher γ, Cp, lower dγ/dT relative to LH2
- LH2 more susceptible to drying out – lower superheat required to initiate boiling

Gas temperature

- Elevating the gas temp. above propellant temp. promotes natural convection across interface, reducing interface temperature, leading to premature breakdown

Gas type $n_{GH2} > n_{GHe}$

- Helium gas: promotes evaporation and thus cooler interface temp.
- Hydrogen gas: promotes condensation and thus warmer interface temp.

Mesh type $n_{325} > n_{450} > n_{510}$

- Interplay between pore diameter, screen thickness, void fraction

$$D_P \propto \sqrt{n_{warp} n_{shute}}, \qquad t = 2d_{shute} + d_{warp}, \qquad \varepsilon = \frac{V_{open}}{V_{total}}$$

Finer meshes = smaller pores, shorter thickness, larger void fraction, easier to exchange heat and mass xfer between gas/liquid prior to visible bubble breaks the screen down.

Conclusions/Implications

1. For all screens and both pressurant gases, elevating the temperature of the pressurant gas acts as a degradation factor on LH2 bubble point

$$\frac{\Delta P_{BP}\left(\Delta T\right)}{\Delta P_{BP}\left(\Delta T=0\right)}=\left(1-n_{screen,gas}\left(T_{GAS}-T_{LIQUID}\right)\right)$$

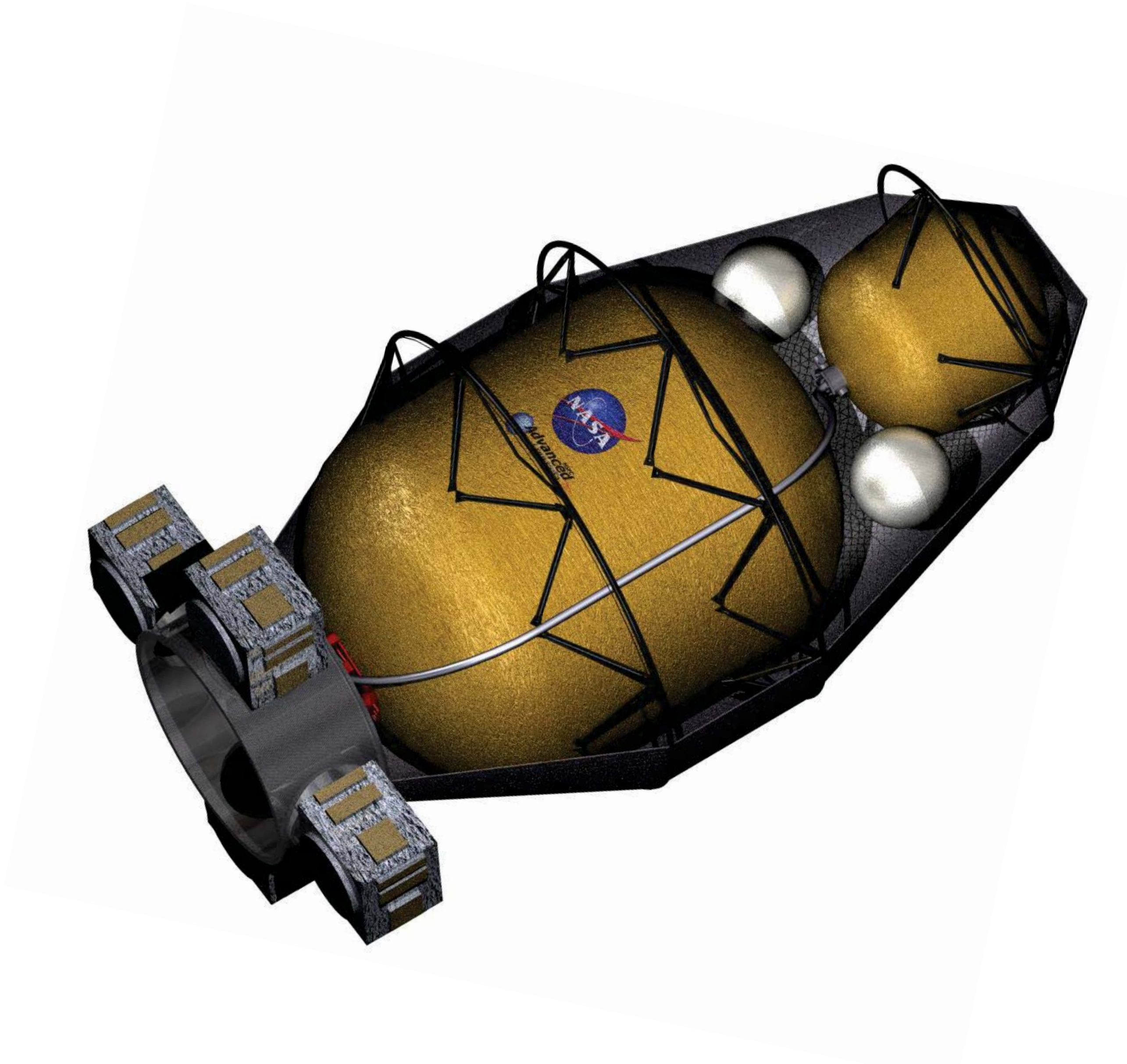
2. Extra margin will be required on top of an already low LH2 bubble point pressure.

   - Warm gas effects on LAD performance won't become an issue in μg until low tank residuals.
   - Careful control of tank pressurization can buy us higher tank expulsion efficiency.

3. Implications for LAD/pressurization system interaction for cryo fuel depots:

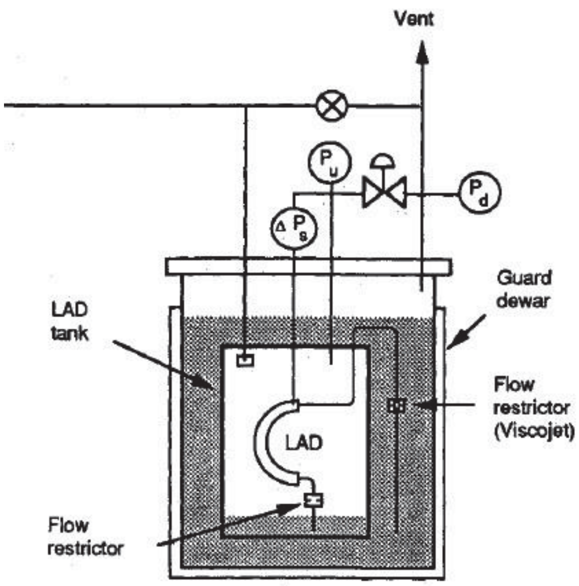
   - Systems level, desire is to have warm gas (packaging)
   - Subsystem level, desire is to have cold gas (improve PMD & transfer performance)

Questions/Comments?



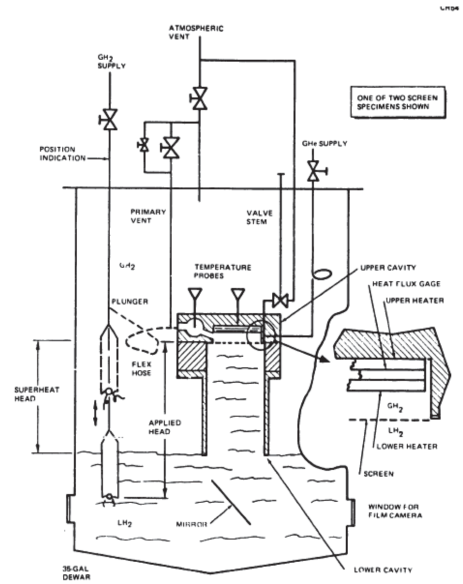
Previous Heated Gas Experiments

Several different configurations have been tested. ***Historical results all over the place.***



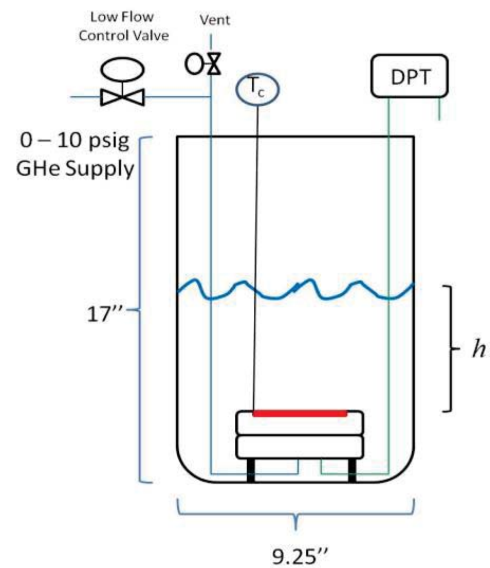
Inverted Outflow

+ Flight representative
- Difficult to control location, direction, temperature of gas (gas is heated, then ullage cooled)
- Data reduction is complicated



Non-inverted Bubble Point

- Hard to control gas flow and gas heating (natural v. forced convection)
- Not flight representative
- Data reduction complicated



Inverted Bubble Point

+ Easy to control gas heating
+ Easy to create uniform temp./pressure rise
+ Data reduction simplified
- Not flight representative

Test purpose: Quantify the effect of warm pressurant gas on the performance of a LAD screen sample